

DECAY WIDTH OF THE PENTAQUARK STATE $\Theta^+(1540)$ WITH QCD SUM RULES

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Abstract

In this article, we take the point of view that the pentaquark state $\Theta^+(1540)$ has negative parity, and choose the diquark-triquark type interpolating current to calculate the strong coupling constant $g_{\Theta NK}$ in the QCD sum rules approach. Our numerical results indicate the values of the strong coupling constant $g_{\Theta NK}$ are very small, $|g_{\Theta NK}| = 0.175 \pm 0.084$, and the width $\Gamma_\Theta < 4MeV$, which can explain the narrow width $\Gamma \leq 10MeV$ naturally.

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Key Words: QCD sum rules, Decay width, Pentaquark

1 Introduction

Several collaborations have reported the observation of the new baryon $\Theta^+(1540)$ with positive strangeness and minimal quark contents $ududs\bar{s}$ [1]. The existence of such an exotic state with narrow width $\Gamma < 15MeV$ and $J^P = \frac{1}{2}^+$ was first predicted in the chiral quark soliton model, where the $\Theta^+(1540)$ is a member of the baryon antidecuplet $\overline{10}$ [2]. The discovery has opened a new field of strong interactions and provides a new opportunity for a deeper understanding of the low energy QCD. Intense theoretical investigations have been motivated to clarify the quantum numbers and to understand the under-structures of the pentaquark state $\Theta^+(1540)$ [3]. The zero of the third component of isospin $I_3 = 0$ and the absence of isospin partners suggest that the baryon $\Theta^+(1540)$ is an isosinglet, while the spin and parity have not been experimentally determined yet and no consensus has ever been reached on the theoretical side. The extremely narrow width below $10MeV$ puts forward a serious challenge to all theoretical models, in the conventional uncorrelated quark models the expected width is of the order of several hundred MeV , since the strong decay $\Theta^+ \rightarrow K^+ N$ is Okubo-Zweig-Iizuka (OZI) super-allowed.

In this article, we take the point of view that the quantum numbers of the pentaquark state $\Theta^+(1540)$ are $J^P = \frac{1}{2}^-$, $I = 0$, $S = +1$, and study its decay width within the framework of the QCD sum rules approach [4, 5, 6].

The article is arranged as follows: we derive the QCD sum rules for the strong coupling constant of the pentaquark state $\Theta^+(1540)$ $g_{\Theta NK}$ in section II; in section III, numerical results; section IV is reserved for conclusion.

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2 QCD sum rules for the coupling constant $g_{\Theta NK}$

In the following, we write down the three-point correlation function [6, 7],

$$\Gamma(p, q) = \int d^4x d^4y e^{ip \cdot x} e^{-iq \cdot y} \langle 0 | T\{\eta_N(x) j_K(y) \bar{\eta}_\Theta(0)\} | 0 \rangle, \quad (1)$$

where the η_N , j_K and $\bar{\eta}_\Theta = \eta_\Theta^+ \gamma^0$ are the interpolating currents for the neutron, K meson and pentaquark state $\Theta^+(1540)$ respectively,

$$\eta_\Theta(0) = \frac{1}{\sqrt{2}} \epsilon^{abc} \{ u_a^T(0) C \gamma_5 d_b(0) \} \{ u_e(0) \bar{s}_e(0) i \gamma_5 d_c(0) - d_e(0) \bar{s}_e(0) i \gamma_5 u_c(0) \}, \quad (2)$$

$$j_K(y) = \bar{s}(y) i \gamma_5 u(y), \quad (3)$$

$$\eta_N(x) = \epsilon^{abc} (d_a^T(x) C \gamma_\mu d_b(x)) \gamma_5 \gamma^\mu u_c(x). \quad (4)$$

For the pentaquark state $\Theta^+(1540)$, we use the diquark-triquark type interpolating current which can give satisfactory mass and stable magnetic moment [7, 8]. The pseudoscalar mesons π and K can be taken as both Goldstone bosons and quark-antiquark bound states, we can use the partial conservation of axial current (PCAC) in constructing the interpolating currents, $\partial_\mu(\bar{s}(x) \gamma^\mu \gamma_5 u(x))$,

$$\begin{aligned} \partial_\mu(\bar{s}(x) \gamma^\mu \gamma_5 u(x)) &= (m_s + m_u) \bar{s}(x) i \gamma_5 u(x), \\ \langle 0 | \partial_\mu(\bar{s}(0) \gamma^\mu \gamma_5 u(0)) | K(q) \rangle &= (m_s + m_u) \langle 0 | \bar{s}(0) i \gamma_5 u(0) | K(q) \rangle, \\ &= f_K q^2 = f_K m_K^2. \end{aligned}$$

If we take the $\bar{s}(x) \gamma^\mu \gamma_5 u(x)$ as the interpolating current, more care has to be taken about the possible contaminations from the axial-vector mesons, furthermore, the calculation will be more tedious (with $\partial_\mu(\bar{s}(x) \gamma^\mu \gamma_5 u(x))$). The matrix element of the pseudoscalar current between the vacuum and K state can be taken as

$$\langle 0 | \bar{s}(0) i \gamma_5 u(0) | K(q) \rangle = \lambda_K = \frac{f_K m_K^2}{m_u + m_s}, \quad (5)$$

the values of the λ_K depend on the masses of the s and u quarks which have uncertainties, our numerical results indicate small variations of those masses will not lead to large changes about the values of the coupling constant $g_{\Theta NK}$. For the neutron, we take the Ioffe current [9]. The Fierz re-ordering of the interpolating currents η_Θ and η_N can lead to the following sub-structures,

$$\eta_N = \epsilon^{abc} \{ (u_a^T C d_b) \gamma_5 d_c - (u_a^T C \gamma_5 d_b) d_c \}, \quad (6)$$

$$\begin{aligned} \eta_\Theta = \frac{1}{4\sqrt{2}} \epsilon^{abc} (u_a^T C \gamma_5 d_b) \{ &- d_c (\bar{s} i \gamma_5 u) - \gamma^\mu d_c (\bar{s} i \gamma_5 \gamma_\mu u) \\ &- \frac{1}{2} \sigma^{\mu\nu} d_c (\bar{s} i \sigma_{\mu\nu} \gamma_5 u) - \gamma^\mu \gamma_5 d_c (\bar{s} i \gamma_\mu u) - \gamma_5 d_c (\bar{s} i u) - (u \leftrightarrow d) \}. \end{aligned} \quad (7)$$

A naive result of the Fierz re-ordering may be the appearance of the reducible contributions with the sub-structure of $udd - u\bar{s}$ (i.e. $N - K$) clusters in the two-point correlation function [10],

$$\Pi(p) = \int d^4x e^{ip \cdot x} \langle 0 | T\{\eta_\Theta(x)\bar{\eta}_\Theta(0)\} | 0 \rangle, \quad (8)$$

however, in our calculations with the interpolating current η_Θ in Eq.(2), no such factorable $udd - u\bar{s}$ terms appear, so there are no reducible $N - K$ contributions to the correlation function $\Pi(p)$. The re-ordering in the Dirac spin space is always accompanied with the color re-arrangement, which involves the underlying dynamics. If we want to factorize out some $N - K$ contributions from the $\Pi(p)$ (with the current η_Θ in Eq.(2)), tedious manipulations about the re-ordering in the color and Dirac spin space must be done. There are no direct $N - K$ (or $udd - u\bar{s}$) components in the interpolating current η_Θ , which can readily decay to the NK final state and result in large width. If the $\Theta^+(1540)$ is really a pentaquark state not a $N - K$ molecule, as the $\Theta^+(1540)$ lies above the NK threshold and no need for additional quark-antiquark pairs creation in decay, the decay must be OZI super-allowed and the width is supposed be large, say, about several hundred MeV; to produce the narrow width, some huge energy barriers are needed to stabilize the $\Theta^+(1540)$ in case the kinematical interpretation can not work here. The appearance of the $N - K$ component in the Fierz re-ordering maybe manifest the possibility (not the probability) of the evolution from the $\Theta^+(1540)$ to the NK final state without net quark-antiquark pairs creation (maybe the quark-antiquark pairs created and annihilated subsequently), which is significantly in contrast to the conventional baryons, however, we have no knowledge about the detailed process of the evolution. The $\Theta^+(1540)$ may evolve to the $N - K$ final state, and the $N - K$ final state is not presented in the components of the initial pentaquark state $\Theta^+(1540)$, how to implement the evolution with small probability involves complex quark-gluon interactions, whether just re-arrangement in the color space, or creation and annihilation of quark-antiquark pairs. In additive constituent quark models, whether or not additional relative P wave is introduced to changed the ground states from negative parity to positivity parity, special configurations are needed to take into account the narrow decay width as results of small overlaps of the internal and external $N - K$ wave-functions [11], the kinematical interpretations based on the color-flavor-spin (i.e. $SU(3)_c \times SU(3)_f \times SU(2)_s$) group theory resort to the possible small overlaps, how to realized the small overlaps needs complex re-ordering in the color-flavor-spin space, if there are really no energy barriers to prevent the re-arrangement. While in the cluster quark models, typically, the diquark-diquark-antiquark model [12] and diquark-triquark model [13], extra barriers, for example, relative P waves, are introduced dynamically to prevent the ready decay. In fact, the re-ordering in the color and Dirac spin space involves complex strong interactions, and we know little now about the dynamics which determine the under-structures of the exotic pentaquark states. The mismatches between the color-flavor-spin states in the initial pentaquark

and final baryon-meson color singlet can result in suppression of the decay naturally [11, 14]. Due to the spontaneous breaking of the chiral symmetry and the Goldstone nature of the pseudoscalar mesons π , K and η , the quarks may have direct interactions with the pseudoscalar mesons, which lead to the success of some chiral quark models. The dominating interactions which determine the exotic pentaquark states be color-spin type $\lambda_i^c \cdot \lambda_j^c \sigma^i \cdot \sigma^j$ or flavor-spin type $\lambda_i^f \cdot \lambda_j^f \sigma^i \cdot \sigma^j$ are still in hot debates [15], the naive Fierz re-ordering can lead to direct $N - K$ component in the $\Theta^+(1540)$ will not work here. If there are really some $N - K$ components in the interpolating current η_Θ , they should be factorized out, the remainder can not have the correct quantum numbers to interpolate the $\Theta^+(1540)$. In the QCD sum rules, we construct the interpolating currents with the same quantum number as the corresponding mesons and baryons, that is enough; the knowledge about the structures of the hadrons can be of much help in the constructing.

In Ref.[5], the narrow decay width is attributed to the minor breaking of chirality conservation, the color re-arrangement due to the hard gluon-exchange can result in strong suppression of the decay, $\Gamma_\Theta \sim \alpha_s^2 < 0|\bar{q}q|0>^2$. In the article, we take quantitative analysis of the decay width within the framework of the QCD sum rules approach.

The diquark-triquark type interpolating current $\eta_\Theta(x)$ is more likely related to a negative parity pentaquark state, in this work, we make assumption that the parity of the $\Theta^+(1540)$ to be negative and study the decay width with the following Lagrangian density,

$$\mathcal{L} = ig_{\Theta NK}\bar{\Theta}KN. \quad (9)$$

According to the basic assumption of current-hadron duality in the QCD sum rules approach [4], we insert a complete series of intermediate states satisfying the unitarity principle with the same quantum numbers as the interpolating currents η_N , j_K and $\bar{\eta}_\Theta$ into the correlation function in Eq.(1) to obtain the hadronic representation. After isolating the double-pole and single-pole terms of the lowest ground states, we get the following result [6, 16],

$$\begin{aligned} \Gamma(p, q) &= \left\{ \frac{g_{\Theta NK}\lambda_\Theta\lambda_N\lambda_K}{m_\Theta^2 - p'^2} \frac{1}{(m_N^2 - p^2)(m_K^2 - q^2)} + \left[\frac{A(p'^2, q^2)}{m_N^2 - p^2} + \frac{B(p'^2, p^2)}{m_K^2 - q^2} \right] + \dots \right\} \\ &\quad \{\sigma^{\mu\nu}q_\mu p_\nu + \dots\} + \dots, \\ &= \left\{ \frac{g_{\Theta NK}\lambda_\Theta\lambda_N\lambda_K}{m_\Theta^2 - p'^2} \int_0^\infty ds \int_0^\infty dt \frac{\delta(s - m_N^2)\delta(t - m_K^2)}{(s - p^2)(t - q^2)} + \right. \\ &\quad \left. \left[\int_0^\infty ds \frac{A(p'^2, q^2)\delta(s - m_N^2)}{s - p^2} + \int_0^\infty dt \frac{B(p'^2, p^2)\delta(t - m_K^2)}{t - q^2} \right] + \dots \right\} \\ &\quad \{\sigma^{\mu\nu}q_\mu p_\nu + \dots\} + \dots, \end{aligned} \quad (10)$$

with

$$A(p'^2, q^2) = \int_{m_K^2}^{\infty} dt \frac{\rho_A(p'^2, t)}{t - q^2}, \quad (11)$$

$$B(p'^2, p^2) = \int_{m_N^2}^{\infty} ds \frac{\rho_B(p'^2, s)}{s - p^2}, \quad (12)$$

where the following definitions have been used,

$$\begin{aligned} \langle 0 | \eta_N | N(p, s) \rangle &= \lambda_N u(p, s), \\ \langle \Theta(p', s') | \bar{\eta}_\Theta | 0 \rangle &= \lambda_\Theta \bar{u}(p', s'). \end{aligned}$$

The coupling constants λ_N and λ_Θ can be determined from the two-point QCD sum rules, for the λ_Θ , we use the correlation function $\Pi(p)$, substitute the η_N for the η_Θ in Eq.(8), we can obtain the λ_N . In this article, we choose the Dirac tensor structure $\sigma^{\mu\nu} q_\mu p_\nu$ for analysis, while in Ref.[6], the authors take the structure $\gamma_5 \sigma^{\mu\nu} q_\mu p_\nu$. Here the residues of the single-pole terms $A(p'^2, q^2)$ and $B(p'^2, p^2)$ have complex dependence on the transitions between the ground states and high resonances (or continuum states). We have no knowledge about the transitions, even the existence of the $\Theta^+(1540)$ is not firmly established. However, the contributions from the pole-continuum transitions are not exponentially suppressed compared with the double-pole terms, even after double Borel transform, furthermore, the contributions can be as large as or larger than the double-pole terms and must be explicitly included in the sum rules. We only have the fact that the $\Theta^+(1540)$ lies a little above the NK threshold, the contributions from the $\Theta^+(1540)$ can be factorized out, so the spectral densities ρ_A and ρ_B can be parameterized as

$$\rho_A(p'^2, t) = \frac{EE(p'^2, t)}{m_{\Theta^+}^2 - p'^2}, \quad (13)$$

$$\rho_B(p'^2, s) = \frac{FF(p'^2, s)}{m_{\Theta^+}^2 - p'^2}. \quad (14)$$

The two unknown functions EE and FF have complex dependence on the transitions between the ground states and high resonances (or continuum states). From the Eqs.(10-14), we can obtain

$$\begin{aligned} \Gamma(p, q) &= \left\{ \frac{g_{\Theta NK} \lambda_\Theta \lambda_N \lambda_K}{m_\Theta^2 - p'^2} \frac{1}{(m_N^2 - p^2)(m_K^2 - q^2)} + \right. \\ &\quad \left. \frac{1}{m_\Theta^2 - p'^2} \left[\frac{1}{m_N^2 - p^2} \int_{m_K^2}^{\infty} dt \frac{EE(p'^2, t)}{t - q^2} + \frac{1}{m_K^2 - q^2} \int_{m_N^2}^{\infty} ds \frac{FF(p'^2, s)}{s - p^2} \right] + \dots \right\} \\ &\quad \{ \sigma^{\mu\nu} q_\mu p_\nu + \dots \} + \dots, \end{aligned} \quad (15)$$

$$\begin{aligned} &= \left\{ \frac{g_{\Theta NK} \lambda_\Theta \lambda_N \lambda_K}{m_\Theta^2 - p'^2} \frac{1}{(m_N^2 - p^2)(m_K^2 - q^2)} + \frac{1}{m_\Theta^2 - p'^2} \left[\frac{CC}{m_N^2 - p^2} + \frac{DD}{m_K^2 - q^2} \right] + \dots \right\} \\ &\quad \{ \sigma^{\mu\nu} q_\mu p_\nu + \dots \} + \dots, \end{aligned} \quad (16)$$

here we introduce two constants CC and DD for convenience,

$$CC = \int_{m_K^2}^{\infty} dt \frac{EE(p'^2, t)}{t - q^2}, \quad (17)$$

$$DD = \int_{m_N^2}^{\infty} ds \frac{FF(p'^2, s)}{s - p^2}. \quad (18)$$

Taking the CC and DD as some unknown constants has smeared the complex dependence on the energy and high resonance masses (or continuum states), which will certainly impair the prediction power. We have no knowledge about the transitions between the pentaquark state $\Theta^+(1540)$ and the excited states (or high resonances, or continuum states), the CC and DD can be taken as free parameters , we choose the suitable values for the CC and DD to eliminate the contaminations from the single-pole terms to obtain the reliable sum rules. The contributions from the single-pole terms may as large as or larger than the double-pole term, in practical manipulations, the CC and DD can be fitted to give stable sum rules with respect to variations of the Borel parameter M^2 in a suitable interval. If the final numerical results are insensitive to the threshold parameters s_0 , t_0 and there really exists a platform with the variations of the Borel parameters M_1^2 and M_2^2 , the predictions make sense.

The calculation of operator product expansion in the deep Euclidean space-time region is straightforward and tedious, here technical details are neglected for simplicity, once the analytical results are obtained, then we can express the correlation functions at the level of quark-gluon degrees of freedom into the following form through dispersion relation,

$$\begin{aligned} \Gamma(p, q) = & \sqrt{2} \left\{ \frac{21m_s}{2^{12}4!\pi^6} \int_0^{s_0} ds \int_0^{t_0} dt \frac{s^2}{s - p^2} \frac{1}{t - q^2} - \frac{11m_s \langle \bar{q}q \rangle^2}{2^7 3\pi^4 p^2} \int_0^{t_0} dt \frac{1}{t - q^2} \right. \\ & \left. + \frac{7 [\langle \bar{q}q \rangle + \langle \bar{s}s \rangle]}{2^9 4!\pi^6 q^2} \int_0^{s_0} ds \frac{s^2}{s - p^2} - \frac{11 [\langle \bar{q}q \rangle^3 + \langle \bar{q}q \rangle^2 \langle \bar{s}s \rangle]}{2^4 3^2 \pi^4 p^2 q^2} \right\} \sigma^{\mu\nu} p_\mu q_\nu + \cdot \end{aligned} \quad (19)$$

We choose $p^2 = p'^2 = -P^2$ and $q^2 = -Q^2$, then take double Borel transform with respect to the variables P^2 and Q^2 respectively, match Eq.(16) with Eq.(19), finally we obtain the sum rules for the strong coupling constant $g_{\Theta NK}$,

$$\begin{aligned} g_{\Theta NK} \lambda_K \lambda_N \lambda_\Theta e^{-\frac{m_\Theta^2}{M_2^2}} e^{-\frac{m_N^2}{M_1^2}} - e^{-\frac{m_K^2}{M_1^2}} &= \\ \sqrt{2} \left\{ \frac{21m_s M_1^6 M_2^2 E_2(s) E_0(t)}{2^{11} 4!\pi^6} + \frac{11m_s \langle \bar{q}q \rangle^2 M_2^2 E_0(t)}{2^7 3\pi^4} \right. \\ \left. - \frac{7 [\langle \bar{q}q \rangle + \langle \bar{s}s \rangle] M_1^6 E_2(s)}{2^8 4!\pi^6} - \frac{11 [\langle \bar{q}q \rangle^3 + \langle \bar{q}q \rangle^2 \langle \bar{s}s \rangle]}{2^4 3^2 \pi^4} \right\}, \end{aligned} \quad (20)$$

where

$$E_n(s) = 1 - e^{-\frac{s_0}{M_1^2}} \sum_{k=0}^n \left(\frac{s_0}{M_1^2} \right)^k \frac{1}{k!},$$

$$E_n(t) = 1 - e^{-\frac{t_0}{M_2^2}} \sum_{k=0}^n \left(\frac{t_0}{M_2^2} \right)^k \frac{1}{k!}.$$

Here the C (proportional to the DD , as the CC terms are eliminated) denotes the contributions from the transitions between the ground and excited states (or high resonances, or continuum states), we can choose the suitable values for C to eliminate the contaminations to obtain the stable sum rules with the variations of the Borel parameters M_1^2 and M_2^2 .

3 Numerical Results

The parameters for the condensates are chosen to be the standard values [4], $\langle \bar{s}s \rangle = (0.8 \pm 0.1)\langle \bar{u}u \rangle$, $\langle \bar{q}q \rangle = \langle \bar{u}u \rangle = \langle \bar{d}d \rangle = -(240 \pm 10 MeV)^3$, $m_u = m_d = 0$ and $m_s = (140 \pm 10) MeV$. Small variations of those condensates will not lead to large changes about the numerical values. The coupling constants are taken as $\lambda_N = (2.4 \pm 0.2) \times 10^{-2} GeV^3$ [9, 16, 17] and $\lambda_\Theta = (1.4 \pm 0.2) \times 10^{-4} GeV^6$ [7] from the two-point QCD sum rules, see Eq.(8) for example. The threshold parameters s_0 and t_0 are chosen to vary between $(1.8 - 2.0) GeV^2$ and $(0.8 - 1.0) GeV^2$ respectively to avoid possible contaminations from high resonances and continuum states. The Borel parameters are taken as $M_2^2 = (1.0 - 1.5) GeV^2$ and $M_1^2 = (1.0 - 2.0) GeV^2$ to obtain the stable sum rules. Finally we obtain the values for the coupling constant $|g_{\Theta NK}|$,

$$|g_{\Theta NK}| = 0.175 \pm 0.084, \quad (21)$$

$$\begin{aligned} \Gamma_\Theta &= \frac{1}{8\pi m_\Theta^3} g_{\Theta NK}^2 [(m_N + m_\Theta)^2 - m_K^2] \sqrt{\lambda(m_\Theta^2, m_N^2, m_K^2)}, \\ &< 4 MeV, \\ \lambda(m_\Theta^2, m_N^2, m_K^2) &= (m_\Theta^2 + m_N^2 - m_K^2)^2 - 4m_\Theta^2 m_N^2. \end{aligned} \quad (22)$$

which can explain the narrow width $\Gamma \leq 10 MeV$ naturally. The values of the coupling constant $g_{\Theta NK}$ with the variations of the threshold parameters (s_0 , t_0) and Borel parameters (M_1^2 , M_2^2) are shown in Fig.1 and Fig.2 for $\langle \bar{s}s \rangle = 0.8\langle \bar{u}u \rangle$, $\langle \bar{q}q \rangle = -(240 MeV)^3$, $m_s = 140 MeV$.

4 Conclusion

In this article, we take the point of view that the pentaquark state $\Theta^+(1540)$ has negative parity, and choose the diquark-triquark type interpolating current to calculate the strong coupling constant $g_{\Theta NK}$ within the framework of the QCD sum

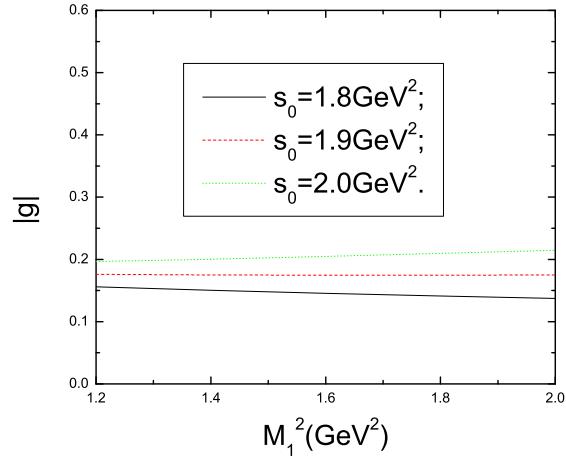


Figure 1: $|g_{\Theta NK}|$ with M_1^2 for $M_2^2 = 1.3 \text{ GeV}^2$, $t_0 = 0.9 \text{ GeV}^2$.

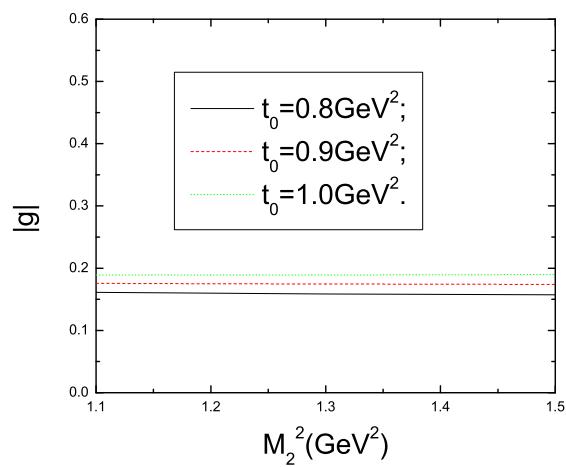


Figure 2: $|g_{\Theta NK}|$ with M_2^2 for $M_1^2 = 1.7 \text{ GeV}^2$, $s_0 = 1.9 \text{ GeV}^2$

rules approach. Our numerical results indicate that values of the strong coupling constant $g_{\Theta NK}$ are very small, $|g_{\Theta NK}| = 0.175 \pm 0.084$, and the width $\Gamma_\Theta < 4 MeV$, which can explain the narrow width $\Gamma \leq 10 MeV$ naturally.

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